

Hadron Correlations and Parton Recombination

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Abstract

Parton recombination has been found to be an extremely useful model to understand hadron production at the Relativistic Heavy Ion Collider. It is particularly important to explore its connections with hard processes. This article reviews some of the aspects of the quark recombination model and places particular emphasis on hadron correlations.

Key words: Ultrarelativistic heavy ion collisions, quantum chromodynamics

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1 Introduction

External probes are valuable tools for testing the properties of plasmas. In relativistic heavy ion physics hard QCD processes and electromagnetic processes take this role and are supposed to unravel the secrets of the quark gluon plasma (QGP). Indeed the first round of experiments at the Relativistic Heavy Ion Collider (RHIC) found impressive evidence for jet quenching, a dramatic energy loss of the leading jet particle [1,2]. Our interpretation of such results relies on the assumptions we make about the applicability of perturbative quantum Chromodynamics (pQCD). The view that momentum transfers of 1 to 2 GeV/ c are sufficient is supported by the success of next-to-leading order pQCD calculations for $p + p$ collisions at RHIC energies. However the answer does depend heavily on the process under consideration.

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Indeed we have now firm experimental evidence that in Au+Au collisions at RHIC most hadrons are not produced from the usual jet fragmentation mechanism up to rather high transverse momenta $P_T \approx 6$ GeV/ c . This makes perturbative hadron production an even rarer process than most of us expected. We want to call hadron production perturbative if it originates from fragmentation of a jet. Of course jets interact heavily with the surrounding medium. In the past it was often assumed that the quenching leads to a reshuffling of energy within the jet cone or a transfer of energy from the jet into the medium without completely destroying the jet. As it turns out, the number of hadrons from surviving jets at intermediate P_T is drowned out by the number of hadrons hadronizing from the bulk fireball via recombination of quarks [3,4,5,6].

The hints from experimental data can be divided into three categories. First, one-particle inclusive hadron spectra show that the chemical composition of the hadrons produced between a P_T of 2 and 6 GeV/ c is not compatible with jet fragmentation. Most notable is the enhancement of baryons as seen in the missing suppression of the nuclear modification factors R_{AA} for baryons and in the various anomalously large baryon/meson ratios [7,8,9]. These results already hint toward a chemically equilibrated source of these hadrons.

Second, the elliptic flow coefficient v_2 follows to very good accuracy a scaling law with respect to the number of valence quarks [9,10]. This is very direct evidence that the observable v_2 is shaped in a deconfined quark phase. A third emerging group of data involves dihadron correlations or associated hadron yields. This data is much more difficult to describe (in any model) than the single hadron spectra. Although jet-like correlations are present at intermediate transverse momenta, the shape of these correlations and the chemical composition can differ strongly from the vacuum [11,12].

The ϕ meson has long been discussed as a good test for the validity of the recombination model [13]. ϕ mesons are as heavy as protons but data from RHIC now impressively confirm that the elliptic flow and nuclear modification factor are very similar to those for kaons [14]. We can now be very sure that the meson vs baryon signature at intermediate P_T is very robust and can neither be explained by an extrapolation of hydrodynamics nor by perturbative jet production and fragmentation.

2 Recombination

In central heavy ion collisions a hot and dense fireball of deconfined quarks and gluons is created. In the recombination model one postulates the existence of thermalized parton degrees of freedom at the phase transition temperature

T_c which recombine or coalesce into hadrons. It has been found to be sufficient to consider the lowest Fock state in each hadron, the valence quarks, which are given constituent masses around 300 MeV.

The spectrum of hadrons can be calculated starting from a convolution of Wigner functions [4]. For a meson with valence (anti)quarks a and b we have

$$\frac{d^3 N_M}{d^3 P} = \sum_{a,b} \int \frac{d^3 R}{(2\pi)^3} \int \frac{d^3 q d^3 r}{(2\pi)^3} \times W_{ab} \left(\mathbf{R} - \frac{\mathbf{r}}{2}, \frac{\mathbf{P}}{2} - \mathbf{q}; \mathbf{R} + \frac{\mathbf{r}}{2}, \frac{\mathbf{P}}{2} + \mathbf{q} \right) \Phi_M(\mathbf{r}, \mathbf{q}). \quad (1)$$

Here W_{ab} is the 2-particle Wigner function for partons a, b and Φ_M is the Wigner function of the meson. The sum runs over all possible parton quantum numbers. For simplicity the parton Wigner function is usually approximated by a product of single particle phase space distributions $W_{ab} = w_a w_b$. Several slightly different implementations of this formalism have been discussed in the literature [4,5,6]. See [15] for earlier reviews.

A very good description of hadron spectra and hadron ratios measured at RHIC can be achieved by combining hadron production from recombination for intermediate transverse momentum with a perturbative calculation using fragmentation and energy loss in the medium [3,4]. Fig. 1 shows the P_T spectrum of π^0 , p , K_0^s and $\Lambda + \bar{\Lambda}$ in central Au+Au collisions obtained in [4]. The agreement with data is very good for $P_T > 2$ GeV/ c . We note that the hadron spectra exhibit an exponential shape up to about 4 GeV/ c for mesons and up to about 6 GeV/ c for baryons, where recombination of thermal quarks dominates. Above, the spectra follow a power-law and production is dominated by fragmentation.

Let us now assume the parton phase exhibits elliptic flow $v_2^P(p_T)$. Recombination makes a prediction for elliptic flow of any hadron species after recombination which is precisely the scaling law mentioned before [16,4]

$$v_2(P_T) = n v_2^P(P_T/n) \quad (2)$$

involving the number n of valence quarks of the hadron. Fig. 2 shows the measured elliptic flow v_2 for several hadron species in a plot with scaled axes v_2/n vs P_T/n . All data points (with exception of the pions) fall on one universal curve. The effect that pions are shifted to lower P_T has been understood [17]. The quark scaling law is an impressive confirmation of the recombination model. It shows that the relevant degrees of freedom at early times in the collision are partons and it proves that these partons behave collectively.

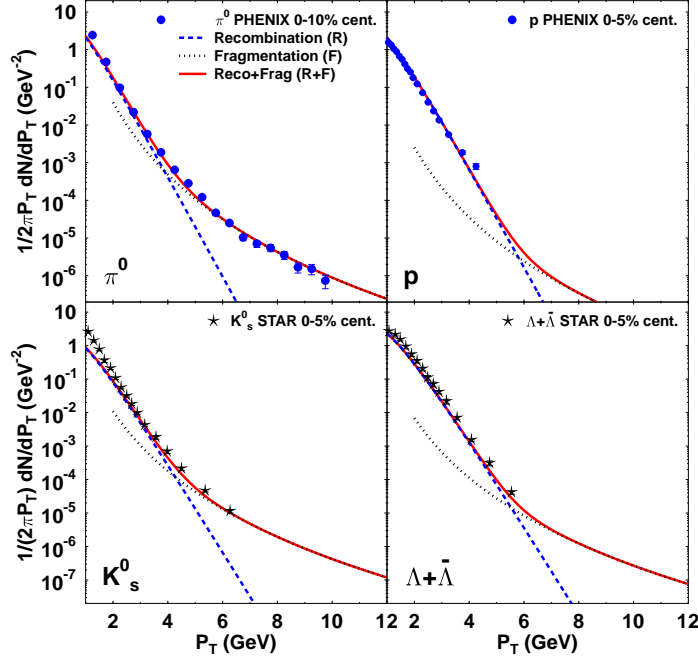


Fig. 1. Spectra of π^0 , p , K_s^0 and $\Lambda + \bar{\Lambda}$ as a function of P_T at midrapidity in central Au+Au collisions at $\sqrt{s} = 200$ GeV [4]. Dashed lines are hadrons from recombination of the thermal phase, dotted line is pQCD with energy loss, solid line is the sum of both contributions. Data are from PHENIX (π^0 , p) [1,7] and STAR (K_s^0 , $\Lambda + \bar{\Lambda}$) [8].

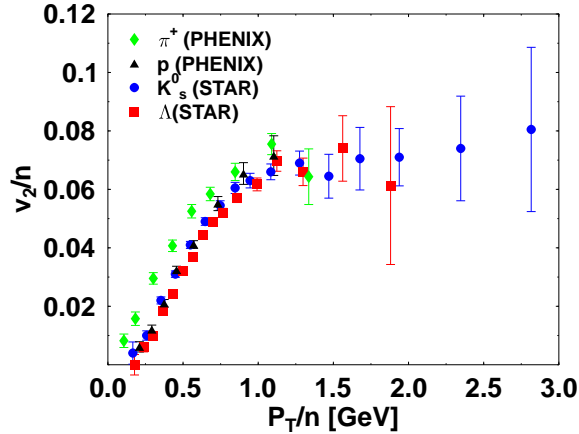


Fig. 2. Elliptic flow v_2 for π^+ , p , K_s^0 and Λ as a function of P_T scaled by the number of valence quarks n vs P_T/n . The data follows a universal curve, impressively confirming the quark scaling law predicted by recombination. Deviations for the pions are discussed in the text. Data are taken from PHENIX (π^+ , p) [10] and STAR (K_s^0 , Λ) [9].

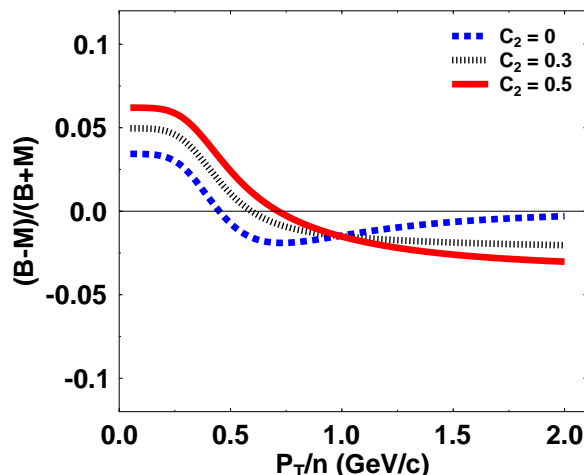


Fig. 3. Scaling violation variable $A = (B - M)/(B + M)$ for three different probabilities C_2 to have an additional parton beyond the valence quark structure. Wave functions of finite width have been used which lead to a scaling violation even in the case $C_2 = 0$ of pure valence quark recombination [18].

It is an interesting question to ask to which accuracy one expects the scaling law for elliptic flow to hold. In particular, are the scaling factors of 2 and 3 indeed excluding any higher Fock states in the hadrons? A recent study found that higher Fock states in an expansion $|p\rangle = a_0|uud\rangle + a_1|uudg\rangle + \dots$ could actually be accommodated [18]. This is in fact trivial for the single-hadron yields from a thermal parton spectrum. They do not change if additional partons are allowed to coalesce. The situation changes for elliptic flow. Higher Fock states with n partons come with their own scaling factor n which seems to destroy the scaling with the number of valence quarks. However a numerical evaluation shows that the correction is surprisingly small. Fig. 3 shows the expected violation of the scaling law using the new asymmetry variable $A = (B - M)/(B + M)$ where B and M are the *scaled* elliptic flow of a meson and a baryon respectively [18]. Generally the violations are smaller than 5%. New data from STAR analyzes scaling violations in the data and finds them to have the predicted sign and order of magnitude [19]. After this study it is clear that there is some room to accommodate gluons or sea quarks during the recombination process. Further investigations in this direction are necessary.

3 Hadron Correlations

One crucial simplification implemented so far is a factorization of any n -parton Wigner function into a product of independent single parton distributions $W_{1,\dots,n} = \prod_{i=1}^n w_i$. By definition this factorization does not permit any correlations between partons. Consequently, no hadron correlations can emerge via

recombination. Originally this factorization was chosen for simplicity and it was justified because single inclusive hadron spectra could be described very well. It has been shown in [20] that modifications of this factorization including correlations between partons lead to correlations between hadrons after recombination. The quality of the single hadron spectra does not suffer. The source of jet-like correlations in the QGP is the strong coupling of jets to the medium. The energy loss is estimated to be up to 14 GeV/fm for a 10 GeV parton [21]. Quenched jets lead to a considerable local heating and create a hot spot inside the fireball. Moreover, the directional information of the jet is preserved. Partons of such a hot spot exhibit jet-like correlations.

The next order extension of the correlation-free factorization in [20] assumes that correlations still are a small effect and that one can restrict them to 2-particle correlations C_{ij} (see also [22]). Then a 4-parton Wigner function can be written

$$W_{1234} \approx w_1 w_2 w_3 w_4 (1 + \sum_{i < j} C_{ij}). \quad (3)$$

The correlation functions C_{ij} between parton i and parton j are non-vanishing only in a subvolume V_c of the fireball. A Gaussian ansatz $C_{ij} \sim c_0 e^{-(\phi_i - \phi_j)^2 / (2\phi_0^2)}$ is chosen to describe correlations in azimuthal angle. The 2-meson yield is given by a convolution of the partonic Wigner function W_{1234} with the Wigner functions Φ_A, Φ_B of the mesons with an additional integration over the hadronization hypersurface [20]. It is assumed that the correlation strength $c_0 \ll 1$ which permits omitting quadratic terms like c_0^2 or $c_0 v_2$.

We can now study the associated yield Y_{AB} for a trigger hadron A in a given kinematic window as a function of the relative azimuthal angle $\Delta\phi$ between the two. One finds

$$2\pi N_A Y_{AB}(\Delta\Phi) = Q \hat{c}_0 e^{-(\Delta\Phi)^2 / (2\phi_0)^2} N_A N_B. \quad (4)$$

The N_i are single particle yields in the kinematic window of the trigger meson or associated meson and $\hat{c}_0 = c_0 V_c / (\tau A_T)$ where τA_T is the hadronization volume. The factor $Q = 4$ (for two mesons) indicates an enhancement of the correlations in the hadron phase compared to the parton phase. The effect is similar to the amplification of elliptic flow by the number n of valence quarks. Q counts the number of possible correlated pairs between the n_A (anti)quarks of meson A and the n_B (anti)quarks of meson B . In the weak correlation limit only single correlations are counted. Apparently one has $Q = n_A n_B$, thus $Q = 6$ for a meson-baryon pair and $Q = 9$ for a baryon-baryon pair.

Fig. 4 shows the associated yield of hadrons integrated in azimuthal angle around the near side ($\Delta\phi = 0$) for the case that the trigger is a baryon (pro-

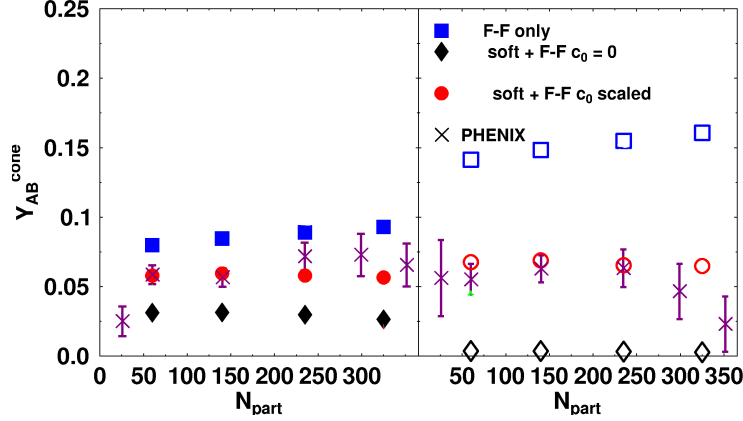


Fig. 4. The associated yield Y_{AB}^{cone} for baryon triggers (right panel) and meson triggers (left panel) as a function of N_{part} . Squares: fragmentation only; diamonds: fragmentation and recombination with $\hat{c}_0 = 0$; circles: the same with $\hat{c}_0 = 0.08 \times 100/N_{part}$; data: PHENIX [12].

ton or antiproton) and a meson (pion or kaon) for different centralities. The kinematic window is $2.5 \text{ GeV}/c \leq P_{TA} \leq 4.0 \text{ GeV}/c$ for trigger particles and $1.7 \text{ GeV}/c \leq P_{TB} \leq 2.5 \text{ GeV}/c$ for associated particles, and $|y_A|, |y_B| < 0.35$. Fig. 4 shows the associated yield with only fragmentation, and fragmentation and recombination both taken into account together with PHENIX data [12]. A good description of the data can be reached assuming a constant correlation volume. The parameters used for the fireball are the same that lead to a good description of single hadron spectra and elliptic flow [4].

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